# Citizen science observations reveal rapid, multi-decadal ecosystem changes in eastern Long Island Sound

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## ARTICLE INFO

## ABSTRACT

Long-term environmental records are among the most valuable assets for understanding the trajectory and consequences of climate change. Here we report on a newly recovered time-series from *Project Oceanology*, a non-profit ocean science organization serving New England schools (USA) since 1972. As part of its educational mission, *Project Oceanology* has routinely and consistently recorded water temperature, pH, and oxygen as well as invertebrate and fish abundance in nearshore waters of the Thames River estuary in eastern Long Island Sound (LIS). We digitized these long-term records to test for decadal trends in abiotic and biotic variables including shifts in species abundance, richness, and diversity. Consistent with previous studies, the data revealed an above-average warming rate of eastern LIS waters over the past four decades ($+0.45$ °C decade$^{-1}$), a non-linear acidification trend twice the global average ($-0.04$ pH units decade$^{-1}$), and a notable decline in whole water-column dissolved oxygen concentrations ($-0.29$ mg L$^{-1}$ decade$^{-1}$). Trawl catches between 1997 and 2016 suggested a significant decrease in overall species diversity and richness, declines in cold-water adapted species such as American lobster (*Homarus americanus*), rock crab (*Cancer irroratus*), and winter flounder (*Pseudopleuronectes americanus*), but concurrent increases in the warm-water decapod *Libinia emarginata* (spider crab). Our study confirmed that Long Island Sound is a rapidly changing urban estuary, while demonstrating the value of long-term observations made by citizen-scientists, educators, and other stakeholders.

## 1. Introduction

Coastal ecosystems are dynamic parts of the world's oceans, providing valuable services to humans in form of nursery habitats for fin- and shellfish, coastal protection, and recreation (Attrill and Power, 2002; Houde and Rutherford, 1993). Coastal ecosystems are also increasingly under combined pressure from global and regional anthropogenic stressors. Globally, excessive carbon dioxide ($CO_2$) emissions have led to land and ocean warming (Mitchell, 1989), with the latter entailing declines in ocean oxygen content and increased stratification (Breitburg et al., 2018; Levin and Breitburg, 2015), while increased $CO_2$ dissolution causes ocean acidification (Doney et al., 2009). Regionally, the problem is often exacerbated by eutrophication from agricultural run-off and increasing coastal populations (Howarth et al., 2000; Mallin et al., 2005) that stimulate primary production and successive microbial respiration, thus intensifying metabolic acidification and deoxygenation in eutrophic coastal systems (Cloern, 2001; Cloern et al., 2014; Nixon, 1995). Warming, acidification, and deoxygenation are the major concurrent symptoms of marine climate change that will likely alter coastal ecosystems in complex and potentially synergistic negative ways (Pörtner et al., 2005).

Exactly how ecosystems have changed and may continue to do so can only be inferred from adequate historical context informed by long-term environmental observations. Environmental record-keeping of e.g., ocean temperature (Chen and Tung, 2018; Nixon et al., 2004), pH (Lauvset et al., 2015), oxygen (Keeling et al., 2010), or the abundance and distribution of plankton (Beaugrand et al., 2009) or fish stocks (Nye et al., 2009) have all collectively contributed to our current understanding of the changes and resilience of marine systems. This is because long-term time-series allow distinguishing natural variability and stochastic events from long-term trends (Collie et al., 2008). While governments and scientific institutions play the leading role in gathering these environmental records, valuable data also have been routinely collected by other entities including industry, educators, and non-profit citizen groups (Bonney et al., 2014). If properly curated, these additional records can substantially broaden the empirical database for regions or parameters that lack traditional monitoring. Examples include citizen-aided monitoring of water quality (Canfield
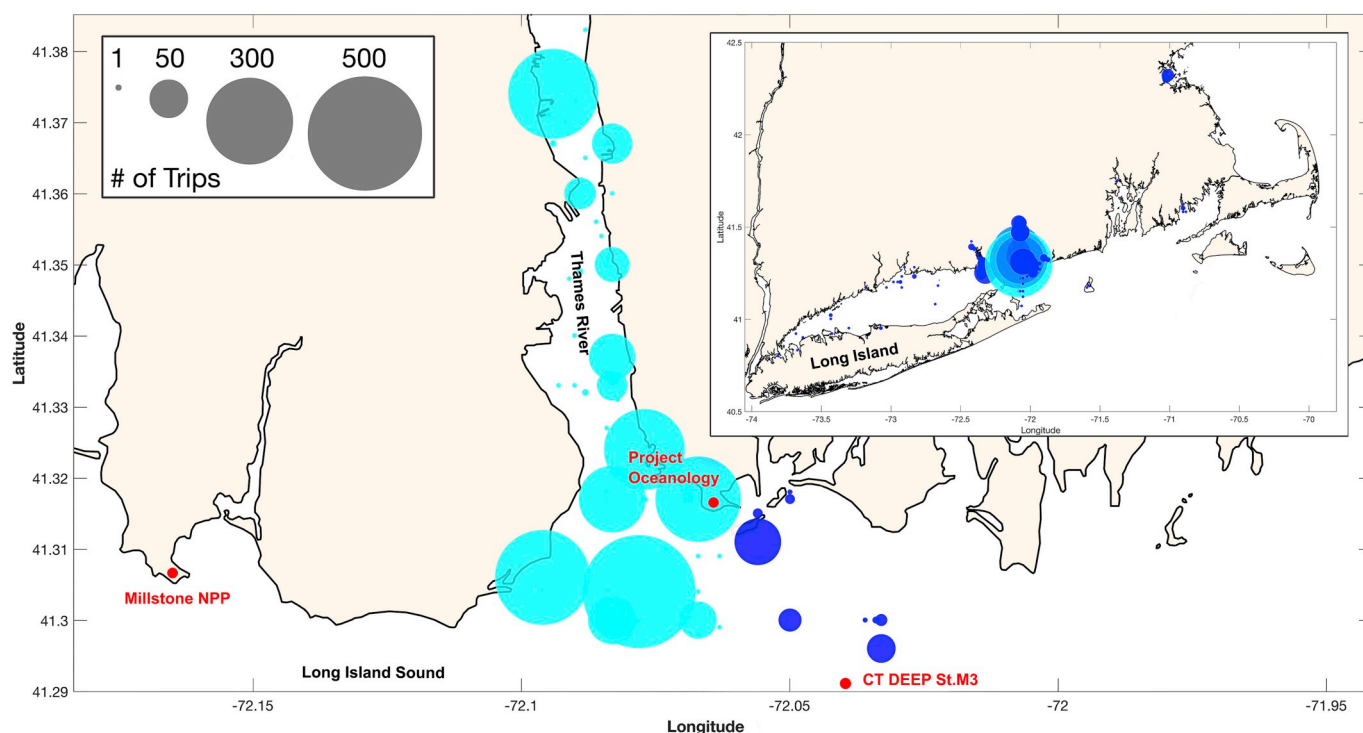
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**Fig. 1.** Spatial extent of sampling effort by Project Oceanology over the past four decades (1972–2016). In total, 51 stations across Long Island Sound, the Connecticut River, Thames River, Fishers Island Sound, and Boston Harbor were sampled (inset); however, efforts were concentrated at the Thames River Mouth, on which this study focused (light blue circles). Red dots depict the locations of Project Oceanology and the Millstone Nuclear Power Plant. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

et al., 2002; Ogata et al., 2009), fish counts by scuba divers (REEF; http://www.reef.org/), spread of invasive species (Gallo and Waitt, 2011), and centuries-old harvest archives to reconstruct historical fish biomass (Hall et al., 2012).

Here we report the recovery and analysis of an environmental time-series recorded by an educational organization from nearshore waters of Long Island Sound (LIS, Northwest Atlantic). LIS is an extensive urban estuary surrounded by a large population (25 million within 75 km; LISS, 2010), for which a number of monitoring efforts by state governments, federal agencies, science institutions, industry, and non-profit organizations already exist (Fig. 1). For example, the Connecticut Department of Energy and Environmental Protection (CT DEEP) conducts monthly water sampling and semi-annual trawl surveys along a standard set of stations as part of the Long Island Sound Study (Howell and Auster, 2012; Staniec and Vlahos, 2017). Since 2004, these efforts have been complemented by the LIS Integrated Coastal Observing System (LISICOS, 2019), which provides continuous buoy measurements of water and atmospheric parameters. While CT DEEP and LISICOS largely focus on offshore waters in the deeper LIS basins, near-shore monitoring of biotic and abiotic parameters has only been conducted in specific locations in western and central LIS. Examples include a high frequency trawl survey within Norwalk Harbor since 1987 (May–October, Crosby et al., 2018) and long-term monitoring of intake waters of a nuclear power plant in Niantic Bay (Millstone Environmental Laboratory, DENC, 2018). Comparable long-term data for nearshore areas east of Niantic Bay and towards the mouth of LIS are lacking.

*Project Oceanology* is a science education organization operating from the campus of University of Connecticut at Avery Point, which is located at the Thames River Mouth (TRM, Fig. 1). For more than 40 years, *Project Oceanology* has educated more than 25,000 students and adults annually by providing hands-on experience of oceanographic methods during boat trips to nearby study areas (Fig. 1). *Project Oceanology* participants have routinely and consistently measured

temperature, pH, oxygen, and many other parameters in the water column. Furthermore, they have recorded the abundance of benthic fish and invertebrate species caught by standard otter trawls. Here we digitized and curated this valuable long-term dataset to examine it for decadal trends in major abiotic variables and shifts in the abundance of single species or species assemblages. We hypothesized that decadal records would show a warming trend greater than the global average but similar to other time-series in Long Island Sound (Howell and Auster, 2012; Staniec and Vlahos, 2017). Given the long-standing concerns about eutrophication in LIS, we also hypothesized that pH and dissolved oxygen (DO) conditions would follow a negative trend. In turn, we expected trawl data to show increases in warm-water adapted over cold-water adapted benthic species.

## 2. Materials and methods

### 2.1. Data collection

Abiotic data were collected from 1974 to 2016 on an average of 40 boat trips per year (range 0–107). The total dataset (3096 entries) encompassed the entire Long Island Sound, but more than half of the data were collected in an area of ~ 10 km$^2$ at the TRM (41°18′59″N 72°04′54″W, n = 1693) on which we focus here. Environmental parameters (DO, temperature) were measured via electronic instruments (YSI 51B, YSI 556; regularly reset to factory defaults) or chemical titrations (pH$_{NIST}$, DO). *Project Oceanology* participants were divided into teams of 3–4 and briefed on measurement methods. All data were collected by participants (students in grades 5–12) under the supervision of trained *Project Oceanology* scientists/educators. Data were curated for quality and consistency in a two-step process. Immediately after each data collection trip, trained educators made note of any sources of error based on their personal observations of data collection during the trip. Approximately 5% of archived records were flagged as untrustworthy as a result of this process and were excluded from this

**Table 1**
Overview of linear regression statistics for abiotic parameters, including effective degrees of freedom (eDF), inherent measurement error (RMSE) and 95% confidence intervals of the estimated trends (*b*).

| Variable | N | DF | eDF | *p* | $r^2$ | RMSE | Trend (*b*) | 95% CI of *b* |
|----------|---|----|----|-----|-------|------|-------------|---------------|
| Temperature | 42 | 41 | 15 | **0.005** | 0.472 | 0.376 | 0.45 °C decade$^{-1}$ | ± 0.28 |
| pH | 42 | 41 | 22 | **0.034** | 0.206 | 0.013 | −0.04 decade$^{-1}$ | ± 0.04 |
| Dissolved Oxygen | 42 | 41 | 22 | **0.020** | 0.242 | 0.431 | −0.29 mg L$^{-1}$ decade$^{-1}$ | ± 0.23 |
| Temp*DO | 1185 | 1184 | N/A | **< 0.001** | 0.611 | N/A | −0.33 mg L$^{-1}$ °C$^{-1}$ | ± 0.01 |
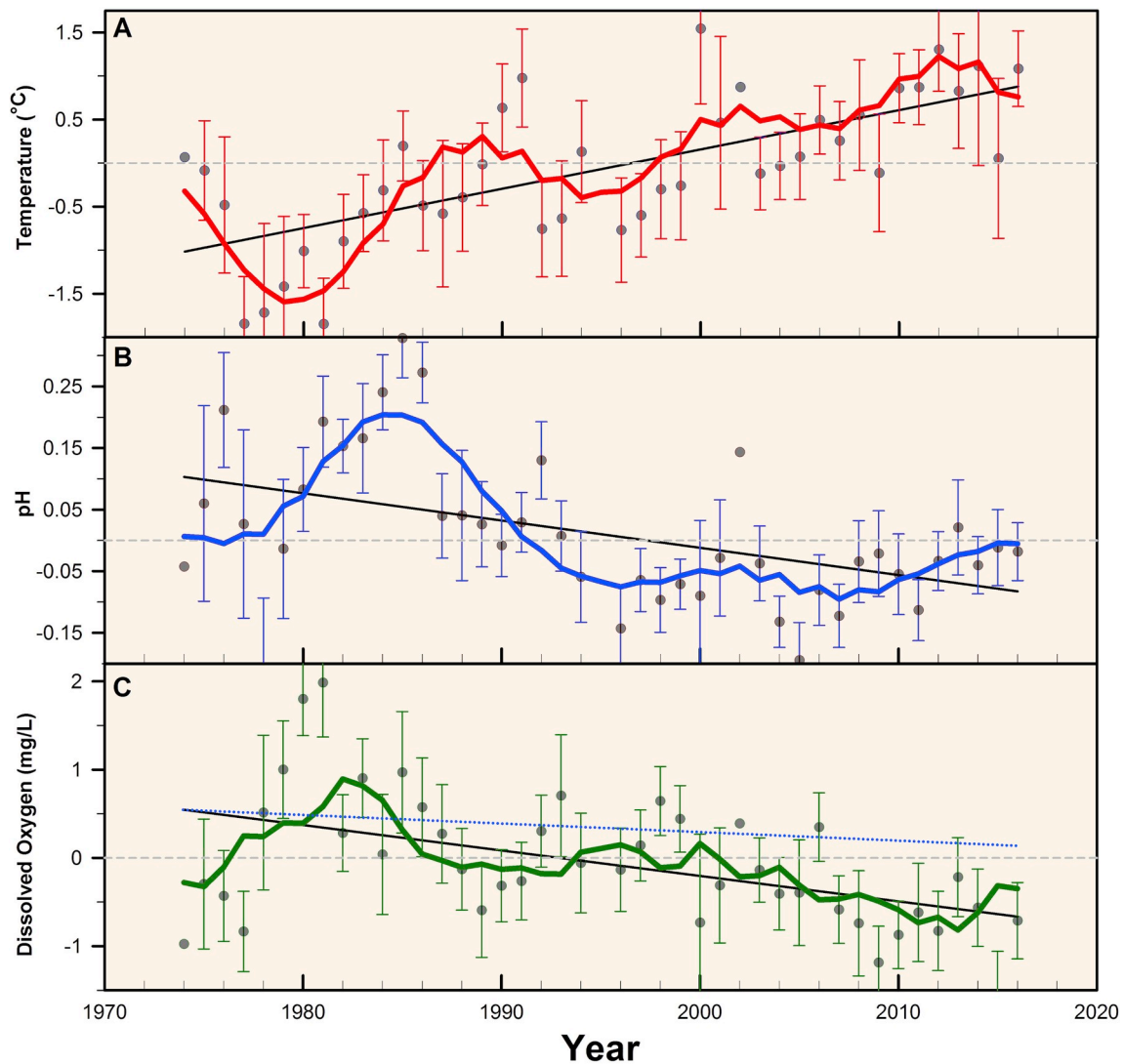


**Fig. 2.** Time series of yearly averaged monthly anomalies of temperature (A), pH (B) and DO conditions (C) at the mouth of the Thames river estuary. Smoothed lines represent decadal trends from wavelet analysis, while black lines show linear regressions. Error bars represent the calculated standard measurement error. The dotted line in panel C depicts the decrease in O$_2$ solubility in seawater of 26.7 psµ (−0.09 mg O$_2$ L$^{-1}$ decade$^{-1}$) expected from the decadal temperature increase alone (panel A, +0.45 °C decade$^{-1}$), using updated equations from Garcia and Gordon (1992).

analysis. After digitization and storage of data in SQL format on the LISICOS server (http://lisicos.uconn.edu/ProjectO/viewfile.php), the dataset was further curated by removing values outside of two standard deviations of the monthly mean (∼3.5% of data removed from each abiotic variable).

Temperature and DO were routinely measured in 1 m vertical intervals, while pH was measured at the surface, middle, and bottom of the water column (average depth 8 m). For this study, we focused on values averaged over the entire water column. Trawl records were available for 670 boat trips, of which 99% occurred between 1997 and 2016. During these trips, an otter trawl was deployed (Wilcox flat trawl,

3 m width, 1.25 cm cod end mesh) for an average of 19.6 min (range: 10–25 min) at ∼2 kts speed over ground. 14% of trawls lacked duration information, and in those cases the calculated average duration was assumed. Onboard educators assisted students in identifying organisms to the lowest taxonomic level possible, using a local identification key (Weiss and Bennett, 1995).

*2.2. Data analysis*

Species abundance was expressed as numbers caught per trawl minute (CPUE). In addition to species-specific CPUEs, CPUEs were also
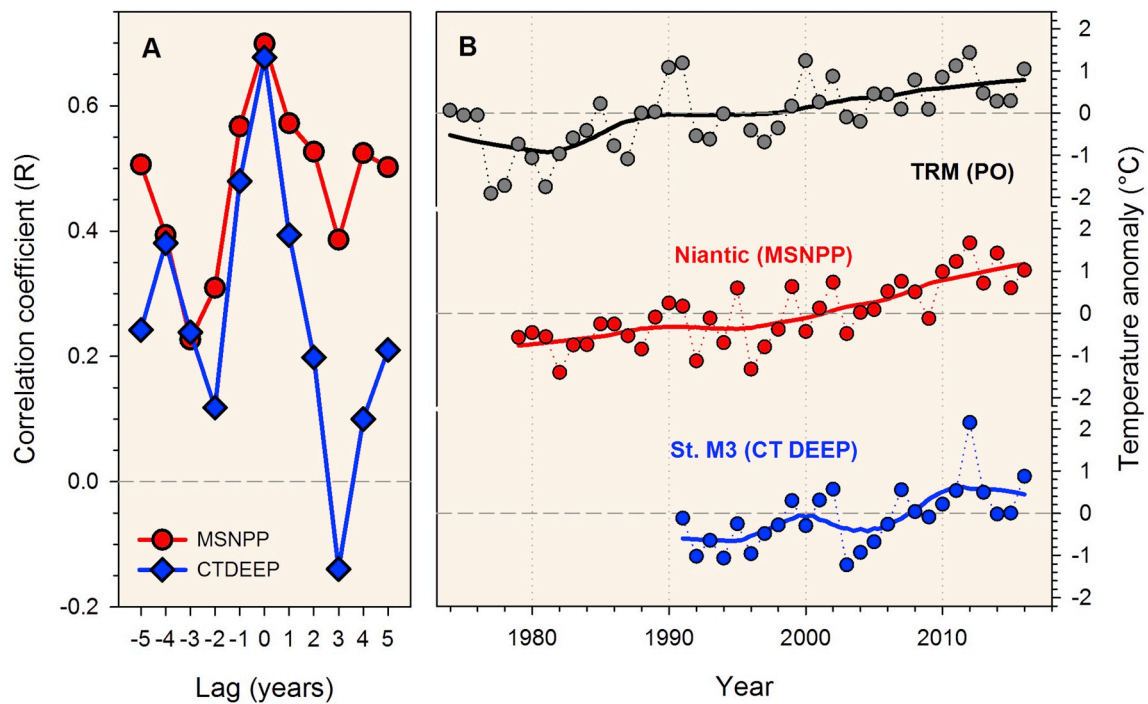
**Fig. 3.** Comparability of the new Project Oceanology time-series for the Thames River Mouth (TRM) to two existing time-series from Niantic Bay (Millstone Nuclear Power Plant, MSNPP) and station M3 (CTDEEP). A: correlogram of annual temperature anomalies between TRM vs. MSNPP (red circles) and TRM vs. CTDEEP (blue diamonds) with 5 years of positive and negative lags. B: Annual temperature anomalies of TRM (black), Niantic (red), and M3 (blue) fitted with a LOESS smoother (40% data bandwidth). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)
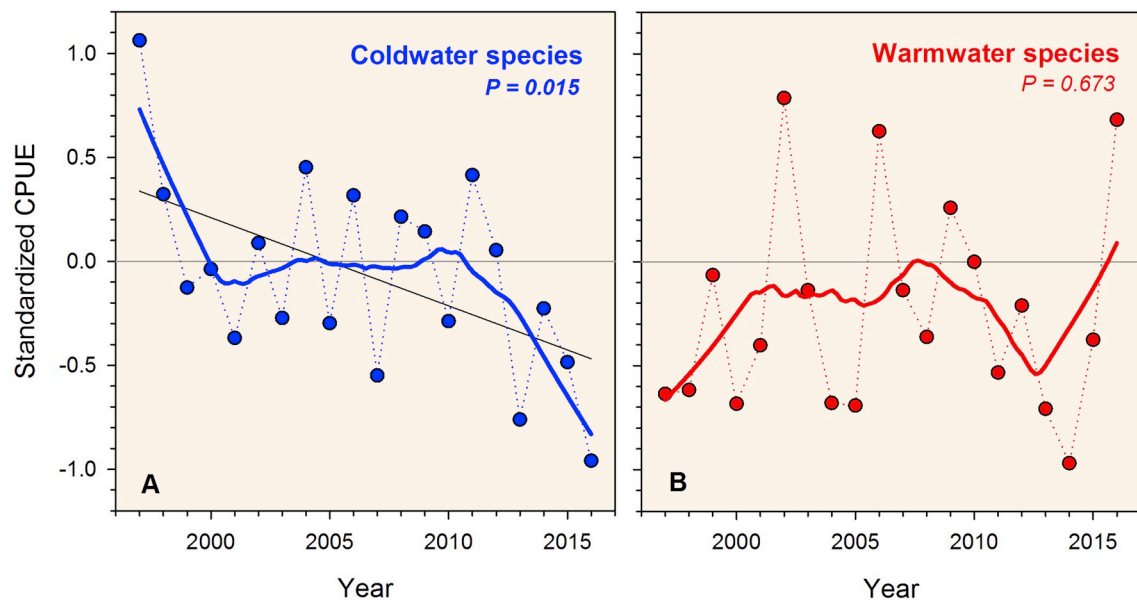


**Fig. 4.** Time series of yearly averaged, standardized catch per unit effort (CPUE, n min trawled$^{-1}$) for invertebrate and vertebrate species classified as either (A) cold-water or (B) warm-water adapted (following Collie et al., 2008). Circles represent annual averages of monthly CPUE means standardized to the overall monthly mean and unit variation. Lines represent LOESS smoothers using a bandwidth of 40% of all data. P-values depict the significance of a linear decadal trend (thin line, if $p < 0.05$).

calculated for three groups: fish, crustaceans, and all other organisms. To assess long-term trends in species assemblages, species collected in trawls were grouped into warm-water vs. cold-water assemblages following definitions by Collie et al. (2008) and Howell and Auster (2012). To characterize the diversity and richness of each trawl, the Shannon Index $H$ (Shannon, 1948) and the Margalef Index $D$ (Margalef, 1958) were calculated as

$$H = -\sum_{i}^{s} p_i \ln p_i \quad \text{(Shannon's } H\text{)}$$

$$D = \frac{n-1}{\ln S} \quad \text{(Margalef's } D\text{)}$$

where $p$ is the proportion of species $i$ of the total catch ($S$) and $n$ is the

**Table 2**
Overview of significant linear regressions for trawl catches of single species, species assemblages, standardized Shannon diversity and Margalef richness indices (1997–2016), including degrees of freedom (DF), adjusted $r^2$, trend estimates ($b$) and their 95% confidence intervals.

| Variable | Species/group | N | DF | $p$ | Adj $r^2$ | Trend ($b$) | 95% CI of $b$ |
|---|---|---|---|---|---|---|---|
| CPUE | Winter flounder | 20 | 18 | < 0.001 | 0.56 | $-0.07$ year$^{-1}$ | ± 0.03 |
|  | Spider crab | 20 | 18 | 0.022 | 0.22 | $+0.04$ year$^{-1}$ | ± 0.04 |
|  | American lobster | 20 | 18 | < 0.001 | 0.54 | $-0.10$ year$^{-1}$ | ± 0.04 |
|  | Rock crab | 20 | 18 | 0.001 | 0.43 | $-0.06$ year$^{-1}$ | ± 0.03 |
|  | Coldwater species | 20 | 18 | 0.015 | 0.25 | $-0.04$ year$^{-1}$ | ± 0.03 |
| Shannon Index, $H$ | Crustaceans | 20 | 18 | 0.004 | 0.34 | $-0.08$ year$^{-1}$ | ± 0.05 |
|  | All groups | 20 | 18 | < 0.001 | 0.49 | $-0.07$ year$^{-1}$ | ± 0.03 |
| Margalef Index, $D$ | Crustaceans | 20 | 18 | < 0.001 | 0.56 | $-0.08$ year$^{-1}$ | ± 0.04 |
|  | All groups | 20 | 18 | 0.001 | 0.45 | $-0.07$ year$^{-1}$ | ± 0.03 |

total number of species caught. $H$ and $D$ were calculated separately for (a) fish, (b) crustaceans, and (c) the entire catch.

Abiotic data (temperature, pH, DO) were first averaged by month, followed by calculating monthly anomalies based on the overall monthly mean across the entire time series. Biotic data (CPUEs, $H$, $D$) were also averaged by month, followed by standardizing them to zero overall monthly means (not all months had trawls) and unit standard deviation of the entire time series. Standardized monthly anomalies were then further aggregated by year, ensuring that each month was weighted evenly in the final mean value used for statistical analysis. To ensure appropriate error propagation from individual measured values to the final mean used for analysis, we calculated the standard error ($SE_{me}$) of the mean, which includes the inherent measurement error, as

$$SE_{me} = \frac{\sqrt{\sigma_s^2 + M^2}}{\sqrt{N}}$$

with $\sigma_s$ being the standard deviation of the sample, $M^2$ the standard measurement error, and N the total number of values. The measurement error for pH was estimated as ± 0.1 units, while measurement errors of temperature and DO were conservatively assumed as ± 1 °C and ± 1 mg L$^{-1}$ DO. We used linear regression of monthly-anomalies of each abiotic variable to test for overall temporal trends. Furthermore, wavelets analysis was used to test for multiannual oscillations in the data and to calculate global and local power spectra, where significant trends would fall within the cone of influence (Torrence and Compo, 1998; Whitney, 2010). A linear regression analysis on low-pass-filtered data for vertically averaged temperature, DO, and pH was conducted. We used an effective degrees of freedom analysis to identify the lag where the squared autocorrelation coefficient crossed a threshold of 0.5, then divided the data length (n = 42) by the lag number to yield the effective degrees of freedom (Table 1).

Last, we used cross-correlograms of annual temperature anomalies (lag range: $-5$ to $+5$ years) to examine the comparability of the *Project Oceanology* time series for the TRM to two other time-series of Long Island Sound; i.e., surface temperature since 1991 at station M3 (CT DEEP) and temperature records of Niantic Bay since 1979 (DENC, 2018). High positive correlations between these time series would suggest comparability of detected long-term trends.

## 3. Results

Temperature increased significantly ($p$ = 0.004, $r^2$ = 0.47, Fig. 2A, Table 1 for all parameter regressions) in the TRM over the past four decades, with an overall warming trend of 0.45 ± 0.28 °C decade$^{-1}$ (95% confidence interval). Overall, pH decreased significantly ($p$ = 0.034, $r^2$ = 0.21) at a rate of $-0.04$ ± 0.04 units decade$^{-1}$ (Fig. 2B); however, the decline was not monotonic, because pH first increased then sharply decreased during the 1980s and at the beginning of the 1990s. DO also decreased significantly at a rate of $-0.29$ ± 0.23 mg L$^{-1}$ decade$^{-1}$ (95% confidence interval) ($p$ = 0.02,

$r^2$ = 0.24, Fig. 2C). Temperature and DO were significantly negatively correlated (Pearson correlation, $p$ < 0.001, $r^2$ = 0.61), while pH was uncorrelated to temperature or DO. The decrease in DO was greater than the reduction in DO expected from increasing temperatures alone (i.e., $-0.09$ mg O$_2$ L$^{-1}$ decade$^{-1}$ given $+0.45$ °C decade$^{-1}$, Fig. 2C; Garcia and Gordon, 1992). Cross-correlograms of annual temperature anomalies between TRM and long-term records of CT DEEP (Station M3) and Niantic Bay (Millstone NPP) showed highest positive correlations (r = 0.70) at lag 0, with sharp decreases in correlation at both positive and negative lags (Fig. 3), thus suggesting consistence between these time series in capturing the overall warming trend in Long Island Sound.

A total of 91 species were caught in the otter trawl over the entire time series (Table S1), with 65 occurring more than once. Spider crabs (*Libinia emarginata*) were the most frequent species on average, being present in 68% of the 670 trawls conducted. Standardized annual CPUEs revealed a significant decline in cold-water species assemblages ($p$ = 0.015) between 1997 and 2016 (Fig. 4A, Table 2), with sharp decreases at the beginning (1997–2001) and end of the time series (2011–2016). During these early and last time intervals, the CPUEs of warm-water species assemblages increased (Fig. 4B), although the overall trend was not statistically significant (Fig. 4B, $p$ = 0.673). Partitioning trawl catches into fish, crustaceans, and other marine organisms showed no significant trends for either group over the past two decades (Fig. 5A–C). However, a large increase in crustacean catches occurred between 2003 and 2011 (Fig. 5B), likely driven by the steep increase in catches of a single species, spider crab (Fig. 6C, $p$ = 0.022). Conversely, American lobster (*Homarus americanus*, Fig. 6A, $p$ < 0.001) and rock crab (*Cancer irroratus*, Fig. 6B, $p$ = 0.001) abundance decreased precipitously over time, with the steepest decline observed at the beginning of the time series. Catches of winter flounder (*Pseudopleuronectes americanus*) decreased steadily between 1997 and 2016 (Fig. 6D, $p$ < 0.001, Table 2, Fig. S1). In the early 1970s, two trawls (excluded from analysis) recorded winter flounder catches of 49 and 145 individuals per trawl, whereas the largest catch between 1997 and 2016 was 26 individuals. The CPUEs of other major species (e.g., scup *Stenotomus chrysops*, summer flounder *Paralichthys dentatus*, longfin inshore squid *Doryteuthis pealeii* Fig. S2) were highly heterogeneous and showed no statistically significant trend over the past two decades. Standardized annual Shannon and Margalef indices revealed significant monotonic declines in whole catch diversity and richness, respectively (Fig. 7C,F, $p$ < 0.001), which appeared to be driven largely by significant decreases in crustacean diversity and richness in the trawls (Fig. 7B,E, $p$ < 0.005, Table 2), whereas no overall diversity and richness trends were found for fish (Fig. 7A,C, $p$ > 0.4).

## 4. Discussion

We recovered a previously unavailable citizen science time-series of abiotic and biotic measurements in Eastern Long Island Sound,
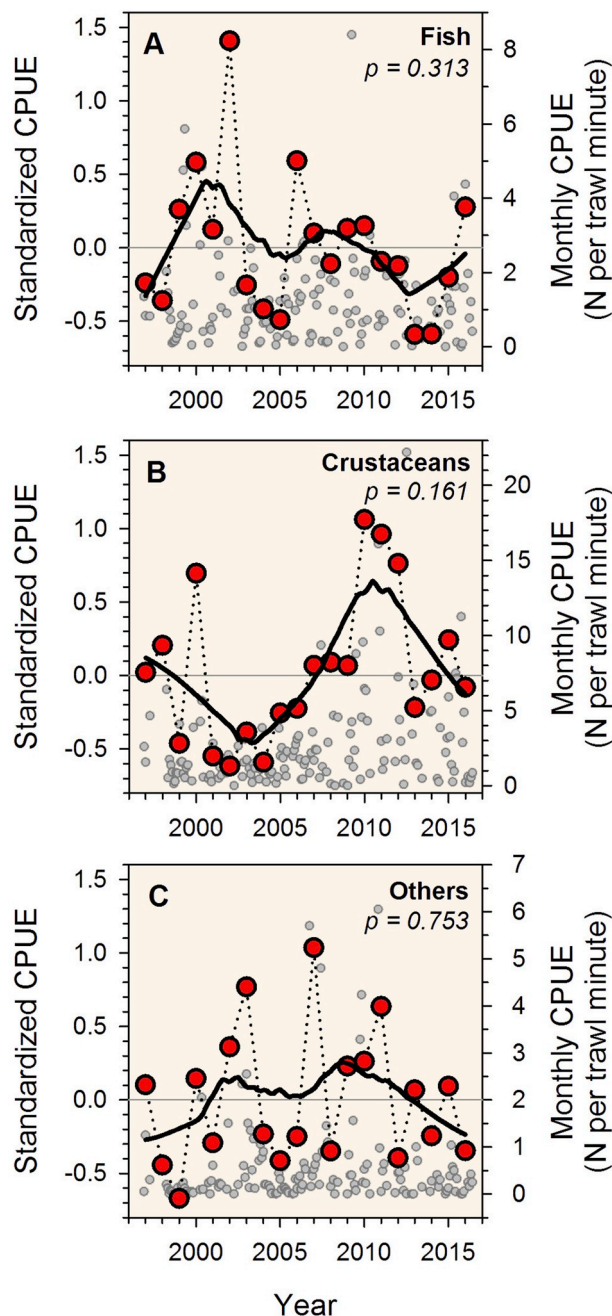
**Fig. 5.** Time series of monthly mean CPUEs (small, grey circles; n min trawled$^{-1}$) and yearly averaged, standardized CPUEs (large red circles) for (A) fish, (B) crustaceans, and (C) other taxa in otter trawl catches between 1997 and 2016. Lines represent LOESS smoothers using a bandwidth of 40% of all data. P-values depict the significance of a linear decadal trend. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

examined it for long-term trends and compared it to other existing time-series in this coastal ecosystem. The data clearly showed that eastern LIS waters have been warming and acidifying faster than the global average, while revealing declines in dissolved oxygen and pronounced shifts in species abundance and diversity. These findings are highly consistent with other long-term datasets of Long Island Sound and the larger Northwest Atlantic region (e.g., Gulf of Maine, Mills et al., 2013; Pershing et al., 2015).

Average water temperatures in the study area (TRM) increased by 0.45 °C decade$^{-1}$, which is more than four times faster than the global

ocean average (0.1 °C decade$^{-1}$, Pershing et al., 2015). Long-term measurements in Niantic Bay suggested similar warming rates of 0.51 °C decade$^{-1}$ (1979–2016) with near-identical short-term trends and inter-annual variability (Landers et al., 2001). In Norwalk harbor (western LIS), nearshore waters have been warming at 0.43 °C decade$^{-1}$ (1987–2016, Crosby et al., 2018). Warming rates for the CTDEEP station M3 were equally consistent (1991–2016, 0.56 °C decade$^{-1}$), while even faster rates of 0.8 °C decade$^{-1}$ were calculated for average surface temperature at CTDEEP stations A4, H4, and M3 between 1991 and 2013 (Staniec and Vlahos, 2017). Slightly lower rates of ∼0.3 °C decade$^{-1}$ were derived by Rice et al. (2014) for the entire Long Island Sound and by Baumann and Doherty (2013) for coastal latitudes of 41–42°N on the US Atlantic coast (1982–2012). The reasons for the extraordinary warming of LIS and the larger Northwest Atlantic shelf region are still debated, but likely involve broad changes in ocean circulation (Caesar et al., 2018; Chen and Tung, 2018) and possibly increased seasonal stratification of coastal waters. Regardless, the *Project Oceanology* time-series corroborated the current notion of Long Island Sound as a rapidly warming coastal ecosystem with likely pronounced consequences for its biota and ecosystem services (O'Donnell et al., 2014).

While global surface oceans have been acidifying monotonically over past decades at an average rate of −0.018 decade$^{-1}$ (Lauvset et al., 2015), the linear negative pH trend found for the TRM was more than twice as steep (−0.040 pH units decade$^{-1}$). However, in open ocean waters pH changes are largely due to increasing $CO_2$ dissolution from the atmosphere (Doney et al., 2009), whereas in coastal waters other drivers including ecosystem metabolism, nutrient, allochthonous carbon, and freshwater input are of much greater importance for pH variability (Baumann and Smith, 2018; Cai et al., 2011; Salisbury et al., 2008). This explains why nearshore pH time-series rarely exhibit monotonic trends; instead, they typically show large interannual fluctuations in response to varying regional factors (Baumann and Smith, 2018; Duarte et al., 2013; Wootton et al., 2008). In the present case, we observed a pH increase in TRM waters until the mid-1980s, followed by a steep pH-decline and then stabilizing or even slightly improving pH conditions towards the end of the time series. The cause of these varying decadal patterns remains speculative; however, we note that the timing of pH stabilization coincided with the success of region-wide efforts to address the problem of eutrophication by reducing nitrogen inputs from point- and non-point sources into Long Island Sound (Latimer et al., 2013). Reducing eutrophication is likely linked to less severe episodes of seasonal hypoxia and acidification – an important management goal for LIS. For comparison, the pH time-series in Niantic Bay suggested a similarly steep initial pH decline during the 1980s and 1990s, but a more substantial pH increase thereafter, thus resulting in a smaller linear trend of −0.018 decade$^{-1}$ (Fig. S3; DENC, 2018).

Apart from pH, eutrophication is a primary concern in urban coastal waters, because it exacerbates the frequency and intensity of seasonal hypoxia (Diaz and Rosenberg, 1995). The severity of the hypoxia problem is known to decrease from western to eastern LIS waters, with the latter typically assumed to remain well oxygenated year-round. However, the long-term data from *Project Oceanology* clearly reveal a negative trend in whole water dissolved oxygen conditions over the past four decades (−0.29 mg L$^{-1}$ decade$^{-1}$), which is consistent with CTDEEP measurements (0.3 mg L$^{-1}$ decade$^{-1}$; Staniec and Vlahos, 2017) and the recently published decadal DO trend in Norwalk harbor to the west (−0.48 mg L$^{-1}$ decade$^{-1}$, Crosby et al., 2018). Importantly, this oxygen loss is approximately three times greater than expected due to rising water temperatures alone (Dam et al., 2010; Garcia and Gordon, 1992). While average conditions remained well above the nominal threshold for hypoxia (2.0 mg L$^{-1}$), these trends suggest an increasing probability of low oxygen events in the future, even in eastern LIS.

With respect to biotic data, available trawl records since 1997 revealed trends in species abundance and diversity, which were highly
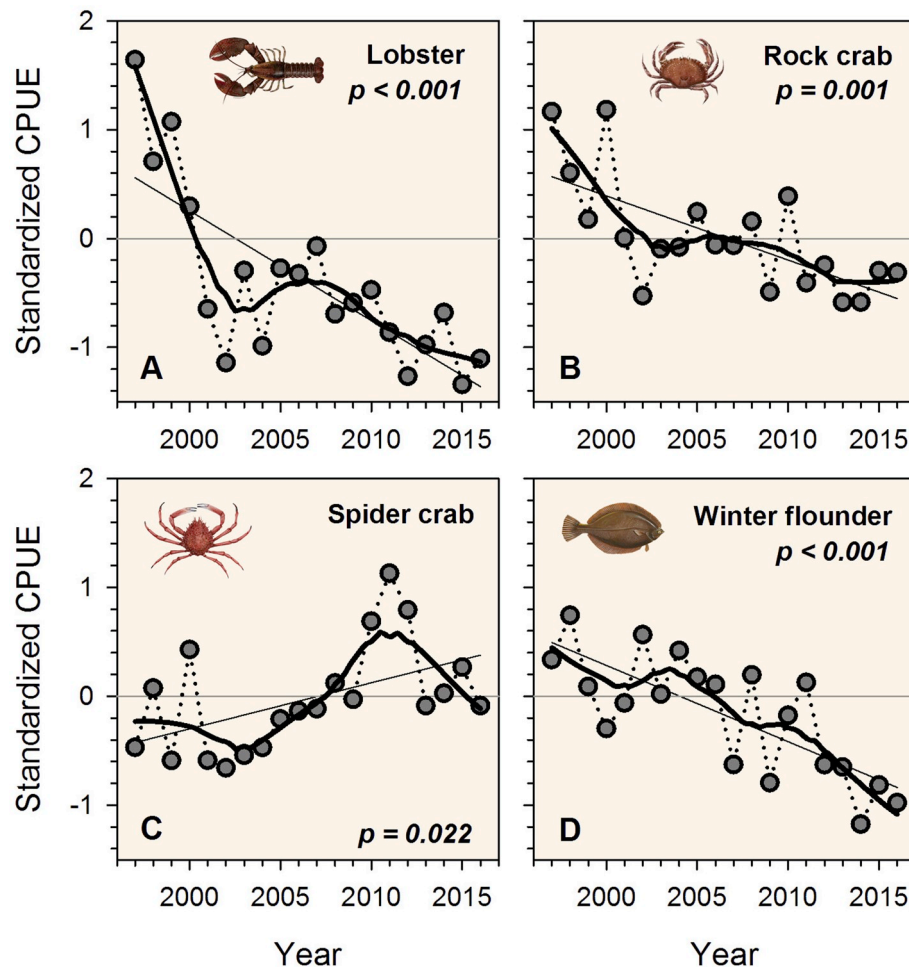
**Fig. 6.** Time series of yearly averaged, standardized CPUEs for (A) American lobster, (B) rock crab, (C) spider crab, and (D) winter flounder. Circles represent annual averages of monthly means standardized to the overall monthly mean and unit variation. Lines represent LOESS smoothers using a bandwidth of 40% of all data. P-values depict the significance of a linear decadal trend (thin line). For monthly mean CPUEs of these species, see Fig. S1.

consistent with other published records (Collie et al., 2008; Crosby et al., 2018; Howell and Auster, 2012; Oviatt, 2004; Pearce and Balcom, 2005). The fast pace of changes may reflect LIS' intermediate position as both a southern boundary of many cold-water species as well as a northern boundary of many warm-water species. Indeed, as expected given the concomitant warming rates, the *Project Oceanology* time-series showed a significant decline in the abundance of cold-water species in the TRM. This is consistent with the shifts from cold-adapted to warm-adapted species evident from monthly CT DEEP trawl records (CTDEEP, 2016; Howell and Auster, 2012) and in Norwalk harbor (Crosby et al., 2018). On the other hand, a pronounced shift from fish to invertebrate species, as reported for Narragansett Bay (1959–2005, Collie et al., 2008) was not evident in our data, possibly because of *Project Oceanology's* more recent and shorter data coverage (1997 to present).

Four species in particular showed significant abundance shifts in our data: American lobster, rock crab, winter flounder, and spider crab. The precipitous decline of lobsters in the TRM is consistent with CTDEEP trawl survey data for LIS (CTDEEP, 2016) and observations across other southern New England since the late nineties (Collie et al., 2008; Pearce and Balcom, 2005). While lobster abundance has increased in the Gulf of Maine to the north (Wahle et al., 2013), the disappearance of LIS lobsters has been attributed to high rates of shell disease (Castro and Angell, 2000), over-fishing (Landers et al., 2001), and increased temperatures (Pearce and Balcom, 2005).

Catches of winter flounder also declined significantly over the past two decades in the TRM, but that decline likely started well before the

1990s, given the few episodic catch records of 100 individuals or more per trawl in the 1970s. Again, this is corroborated by CT DEEP survey data (CTDEEP, 2016; Howell and Auster, 2012), data from Norwalk harbor (Crosby et al., 2018), and separate collections in the upper TRM estuary by the US Coast Guard Academy (1974–2015), monitoring juvenile winter flounder abundance (personal communication K. Mrakovich). A subsequent long-term analysis indicated that the decline and persistent depression of LIS winter flounder may in part be due to increased prey competition in adults and increased predation mortality in juveniles due to the increase of mid-Atlantic fish species in the sound (Howell et al., 2016).

By contrast, the *Project Oceanology* data set revealed significant increases in catches of spider crab, a warm-water crustacean that has increasingly dominated otter trawl catches in the TRM in recent years. Similar increases have been observed at other LIS sites (CTDEEP, 2016) and in Narragansett Bay (1959–2005, Collie et al., 2008). In addition to this species' higher thermal tolerance, its increasing abundance in southern New England waters may be due to their resilience to intermittent hypoxia (Burnett, 1979), their effective use of decorative cover as a method of predator evasion (Wicksten, 1993), decreased competition with other large benthic crustaceans such as lobster, and the lack of a commercial or recreational fishery. An ecological shift from lobsters to spider crabs as the most abundant large benthic scavenger in Long Island Sound could have profound trophic consequences. Spider crabs are far more herbivorous than lobsters (Conklin, 1995) and other large benthic crabs (Ropes, 1989). Lobsters are thought to be a
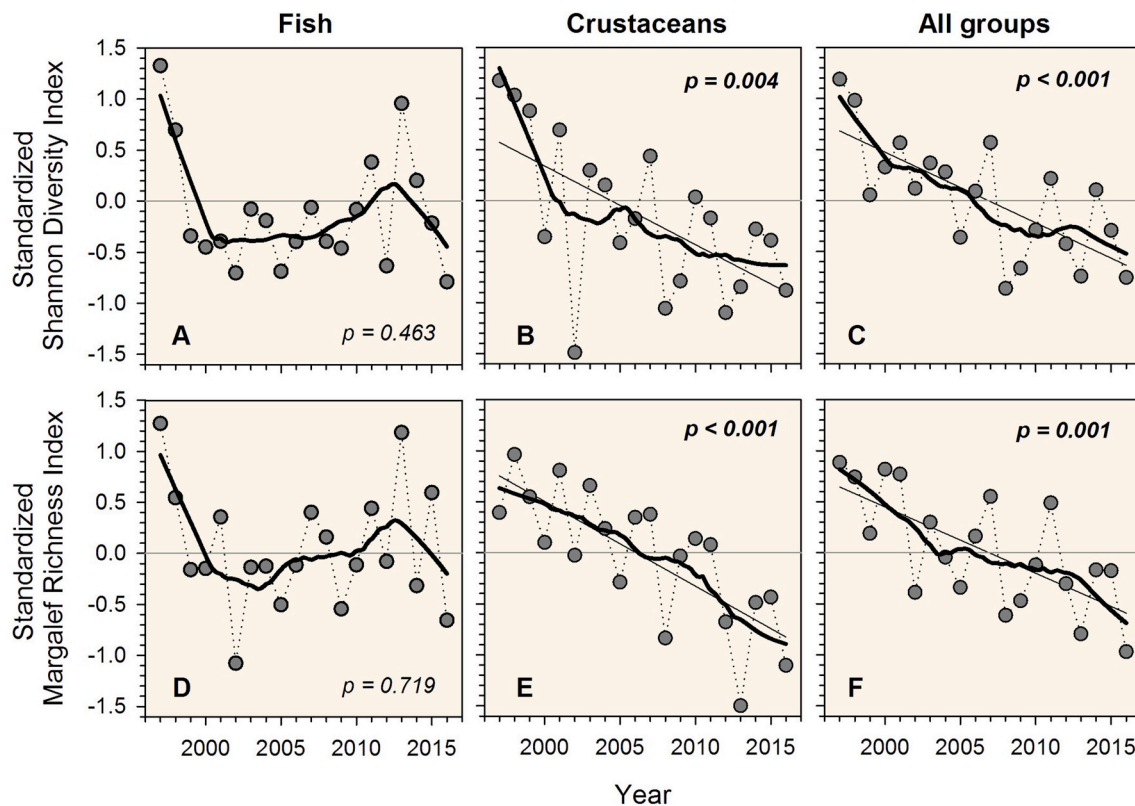
**Fig. 7.** Time series of yearly averaged, standardized (A–C) Shannon diversity indices and (D–F) Margalef species richness indices for fish, crustaceans and across all taxa caught in otter trawls between 1997 and 2016. Lines represent LOESS smoothers using a bandwidth of 40% of all data. P-values depict the significance of a linear decadal trend (thin line).

preferred prey species for large predatory groundfish ranging from historically abundant cod populations (*Gadus morhua*; Lawton and Lavalli, 1995) to currently increasing populations of black sea bass (*Centropristus striata*; Bell et al., 2014; Byron and Link, 2010). There is no fishery for spider crabs, which have smaller claws and less meat than lobsters or cancer crabs, and it is unclear whether spider crabs constitute a significant component of fish diets.

We did not observe significant changes in abundance of several major organisms currently thought to be undergoing northern range expansions. These include blue crabs (*Callinectes sapidus*; Johnson, 2015), scup (*Stenotomus chrysops*), and fluke (*Paralichthys dentatus*; Bell et al., 2014). The time scale or the heterogeneous nature of the *Project Oceanology* dataset may have masked some changes in community composition. Some species may have shifted further onto the continental shelf and did not affect inshore populations in LIS. Northern range shifts can be climate-related, but may also be driven by species-specific changes in commercial fishing pressure or fisheries management (Bell et al, 2014). This suggests that shifts in community composition may be highly localized.

Consistent with Crosby et al. (2018), our study found significant overall declines in species diversity and richness in the TRM, owing largely to declines in both indices for crustacean catches. However, these declines were not associated with lower crustacean abundance, largely because the decreases in species like American lobster or rock crab were compensated by increases in spider crabs. Still, declines in crustacean diversity and richness suggest the potential for reduced functional redundancy and thus lower ecosystem resiliency and services that humans in the region depend on. Fish diversity and richness, on the other hand, remained relatively stable over the study period, suggesting increasing compensation of declining cold-water species (e.g., winter flounder) by temperate, more southern fish assemblages (Auster and Link, 2009).

In conclusion, this study contributed a valuable new data trove of long-term abiotic and biotic observations in the urban estuary of LIS, thereby highlighting the fast pace of environmental change that this coastal ecosystem has experienced over the past four decades. This particular time-series filled a gap for nearshore biotic and abiotic observations in eastern LIS, and by corroborating observations from western, central, and offshore LIS sites strengthened our broader-scale understanding of marine climate change on the Northwest Atlantic shelf. The data are noteworthy, too, for being collected by hundreds of thousands of students, teachers, and members of the public over the past 40 years. To us, this reflects a growing recognition that anticipating complex consequences of marine climate change truly requires the integration of all available information that different entities collect passively or actively about their environment. When data from multiple sources can be integrated, they often produce better-constrained trends and increased confidence in resulting predictions ("Big Data" theory, Mayer-Schoenberger and Cukier, 2013). In the case of *Project Oceanology*, the consistency in trends between this and other expert time-series clearly supports this idea.

### Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marenvres.2019.03.007.

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